Combination of searches for singly produced Vector-Like Quarks with the ATLAS detector

Adrian Rubio Jimenez

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XVI CPAN DAYS

Outline

Motivation	• What are the Vector-Like Quarks? • Common assumptions. • Production modes at the LHC.
Channels analysed	• Summary of the individual analyses.
Combination strategy and results	• Systematics treatment • Improvement from individual analyses. • Exclusion limits.
Conclusions	• Summary and impact of the results.

Outline

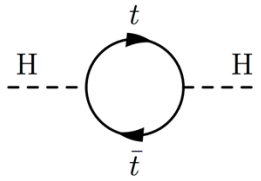
- Motivation
  - What are the Vector-Like Quarks?
  - Common assumptions.
  - Production modes at the LHC.
- Channels analysed
- Combination strategy and results
- Conclusions

What are the Vector-Like Quarks?

- Hierarchy problem:

$$m_H^2 = m_{H,0}^2 + \delta m_H^2$$

$$\delta m_H^2 \propto \int_0^{\Lambda_c} \frac{d^4p}{p^2} \propto \Lambda_c^2$$



- Vector-Like Quarks (VLQs) appear in some BSM models to solve the mass hierarchy problem.
- **Vector-like**: same EW transformations for left- and rigth-handed components.
- **Quarks**: colour-triplets, spin-1/2 particles with same strong coupling.
- Spectrum of VLQs: $X_{+5/3}$, $\mathbf{T_{+2/3}}$, $\mathbf{B_{-1/3}}$, $Y_{-4/3}$.
- Still allowed by constraints on 4th generation of quarks.
- A gauge-invariant Dirac mass term is possible.

Common assumptions in LHC searches

- Minimal assumptions in most Run-1 and Run-2 searches:
  - No couplings to other BSM particles.
  - Narrow Width Approximation is required to ensure that theoretical computations remain valid. → **Interpreting results for $\Gamma/m_Q < 50\%$**
  - Coupling exclusively to third generation of quarks. → **BR(Q -> Hq) + BR(Q -> Zq) + BR(Q -> Wq') = 1**
  - In the large mass limit (~ TeV), Goldstone Equivalence theorem. → **BR(Q -> Hq) = BR(Q -> Zq)**
  - One SU(2) multiplet at a time is assumed.
  - Standard Model couplings are not modified by the presence of VLQs.
  - If the scalar sector only contains $SU(2)_L$ doublets, 7 gauge-covariant SU(2) multiplets are possible:

Multiplet	T	B	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
Hypercharge	$+2/3$	$-1/3$	$+1/6$	$+7/6$	$-5/6$	$+2/3$	$-1/3$
Weak isospin	0	0	1/2	1/2	1/2	1	1
Color charge	1	1	1	1	1	1	1

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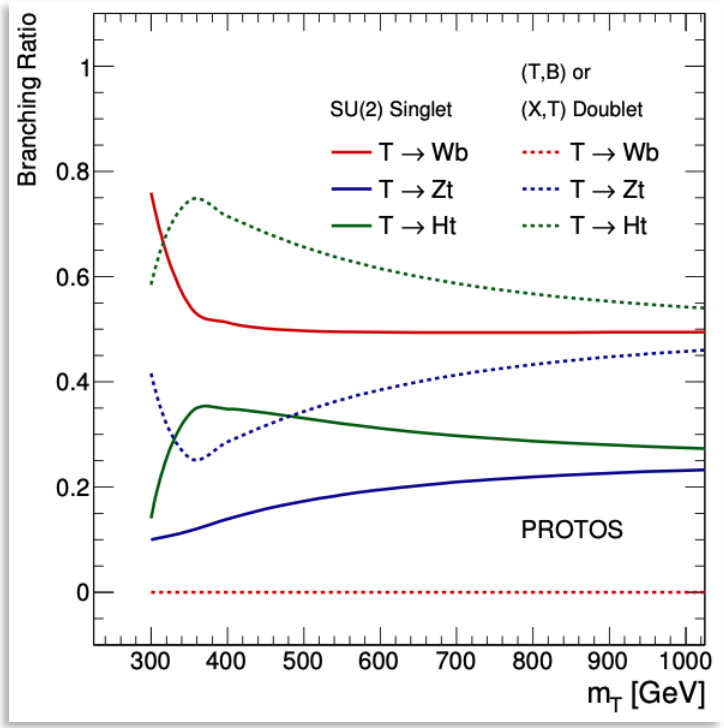
Top partner



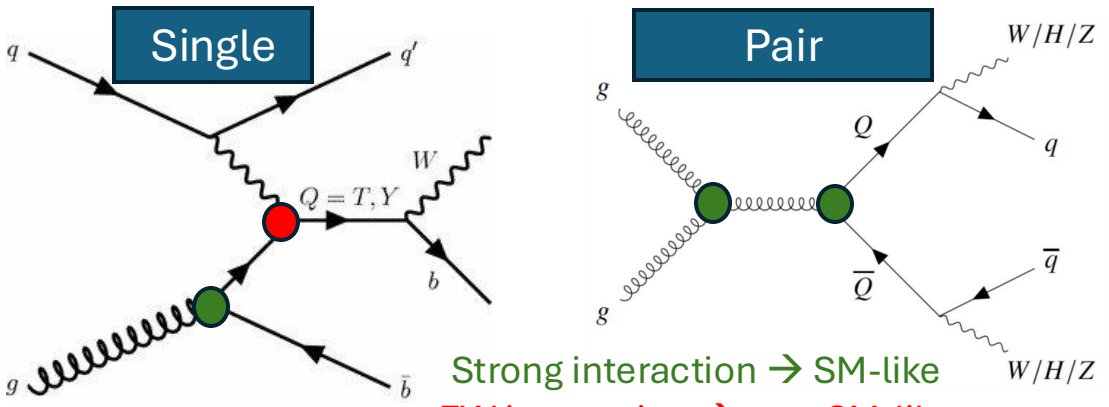
JHEP11(2014)104

T singlet: BR(T->Zt)=BR(T->Ht)=0.25

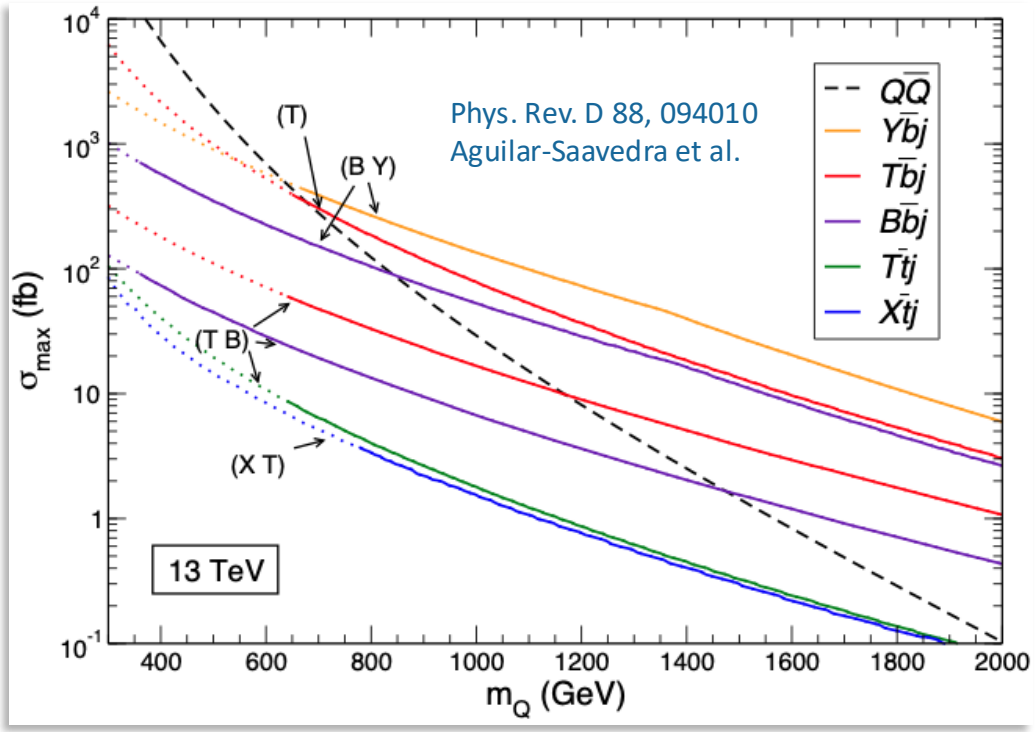
T doublet: BR(T->Zt)=BR(T->Ht)=0.5

VLQs at the LHC

- Two production modes at the LHC:
  - Pair production: dominant for low masses, it only depends on m_Q: $\boldsymbol{\sigma(\alpha_S, m_Q)}$
  - Single production: dominant for large masses, it depends on m_Q and **non-standard EW couplings**.



Strong interaction → SM-like
EW interaction → non-SM-like



- Simplified Lagrangian to interpret the results on few parameters.
  - $\boldsymbol{\sigma(\kappa, m_Q)}$, with $\boldsymbol{\kappa}$ the overall coupling to SM bosons.
  - $\boldsymbol{\Gamma}/m_Q \propto \kappa^2 m_Q^2$
  - Relative couplings ξ_W, ξ_Z, ξ_H (equivalent to the branching ratios in the large mass limit).

Current constraints

- Stringent constraints are being established by ATLAS and CMS.
- Wide range of final states for **singly-produced VLQs** explored by ATLAS:
  - B → bH (H→γγ; H→bb).
  - T/Y → Wb (W→ℓν; W→qq).
  - **T → Ht/Zt (Z→νν; Z→ℓℓ; Z→qq). This talk!!**
- **This combination set the most stringent limits on Vector-like Top quarks to date: Paper**

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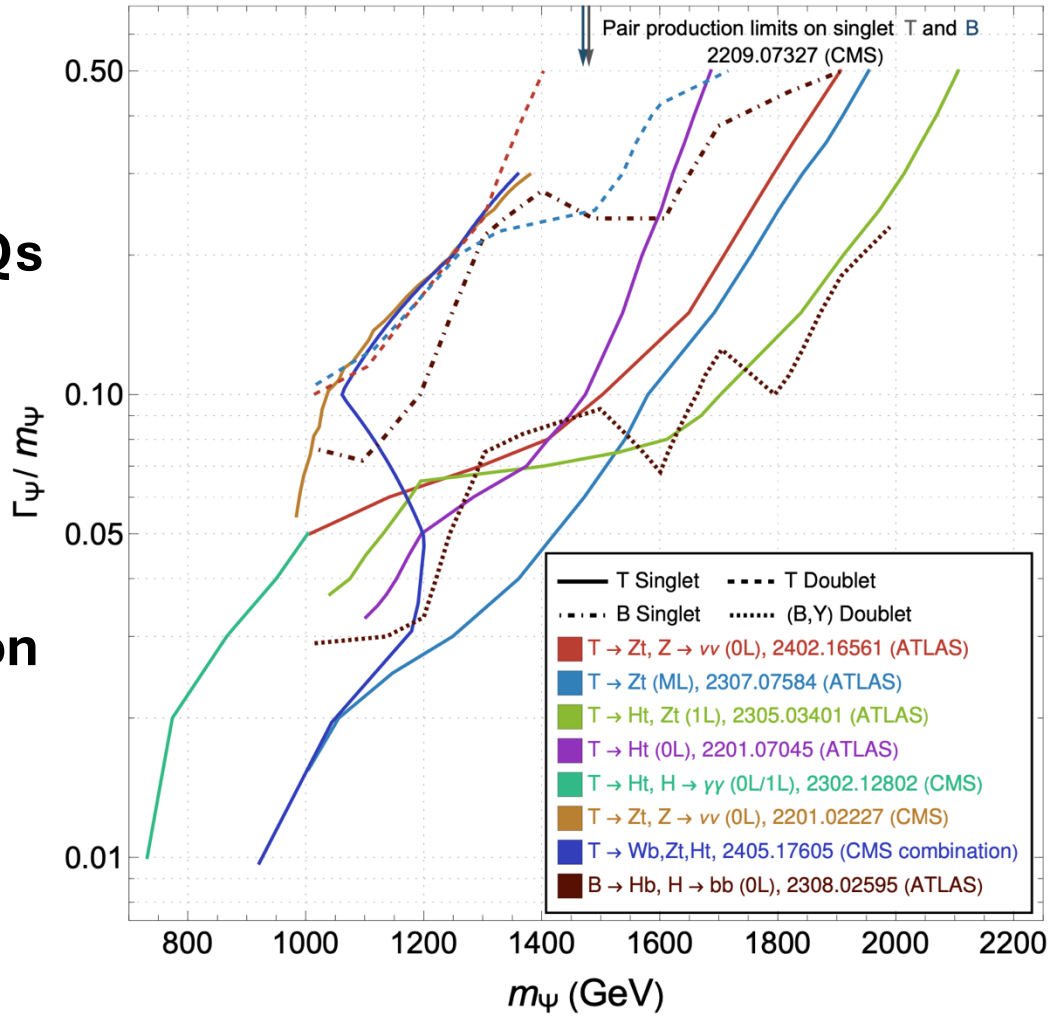

Outline

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Channels analysed

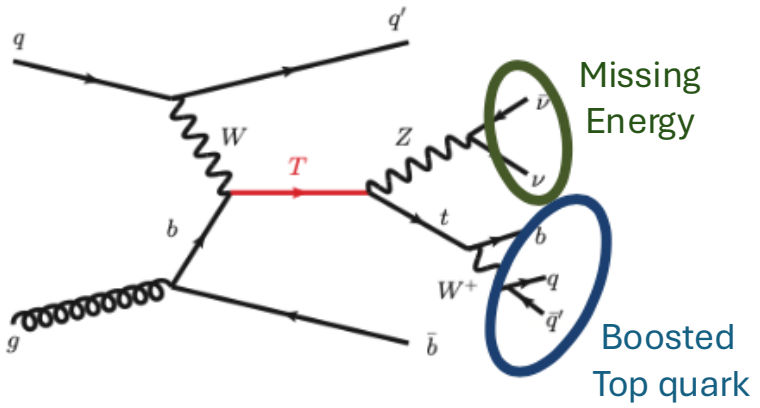
- Summary of the individual analyses.

Combination strategy and results

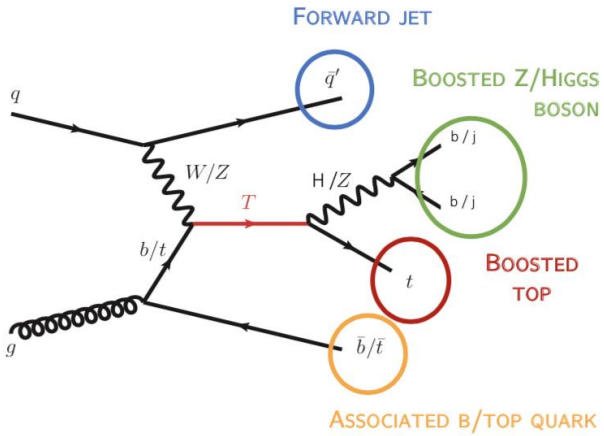
Conclusions

Analyses to combine

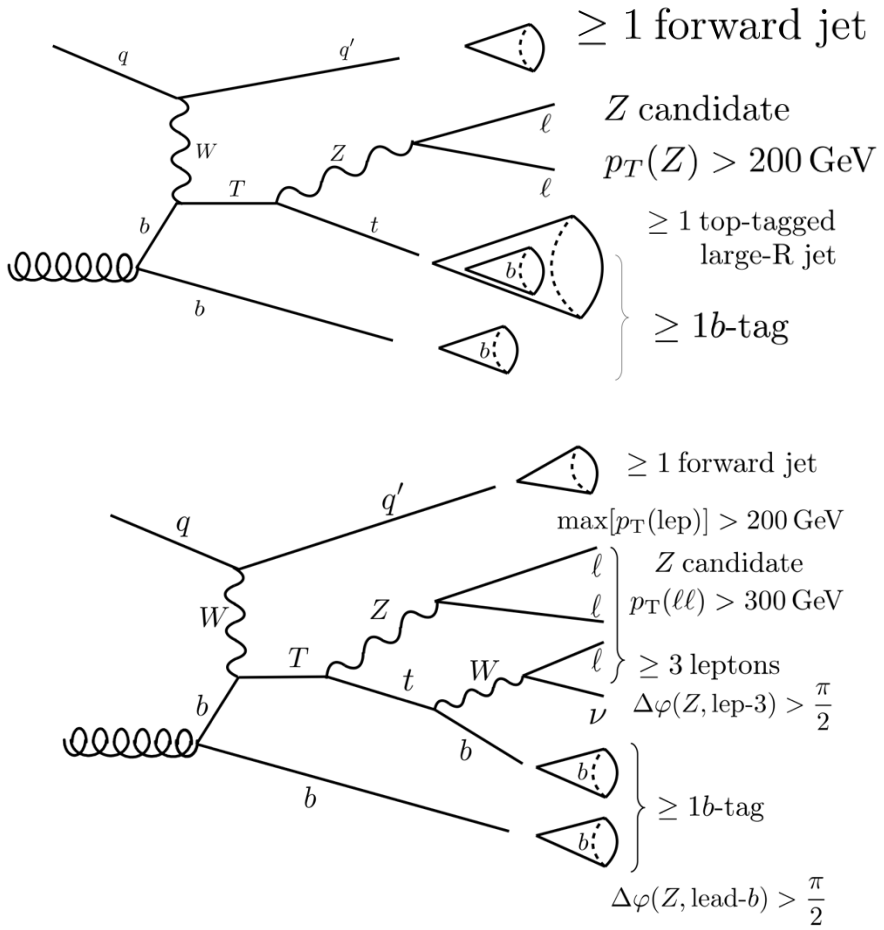
Mono-top (**0 lepton**)



Ht/Zt (**1 lepton**)



OSML (**2 & 3 leptons**)

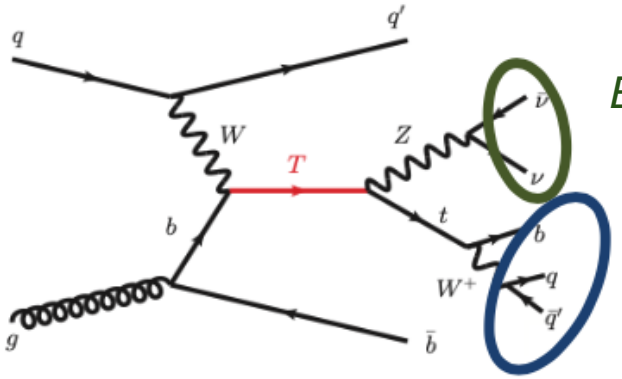


- **Orthogonal final states** by lepton multiplicity.
- Exploring both **SU(2) singlet** and **doublet** scenarios.
- Setting limits to same observables: $\sigma(\kappa, m_{VLQ})$

Mono-top analysis

Publication: JHEP05(2024)263

Preselection

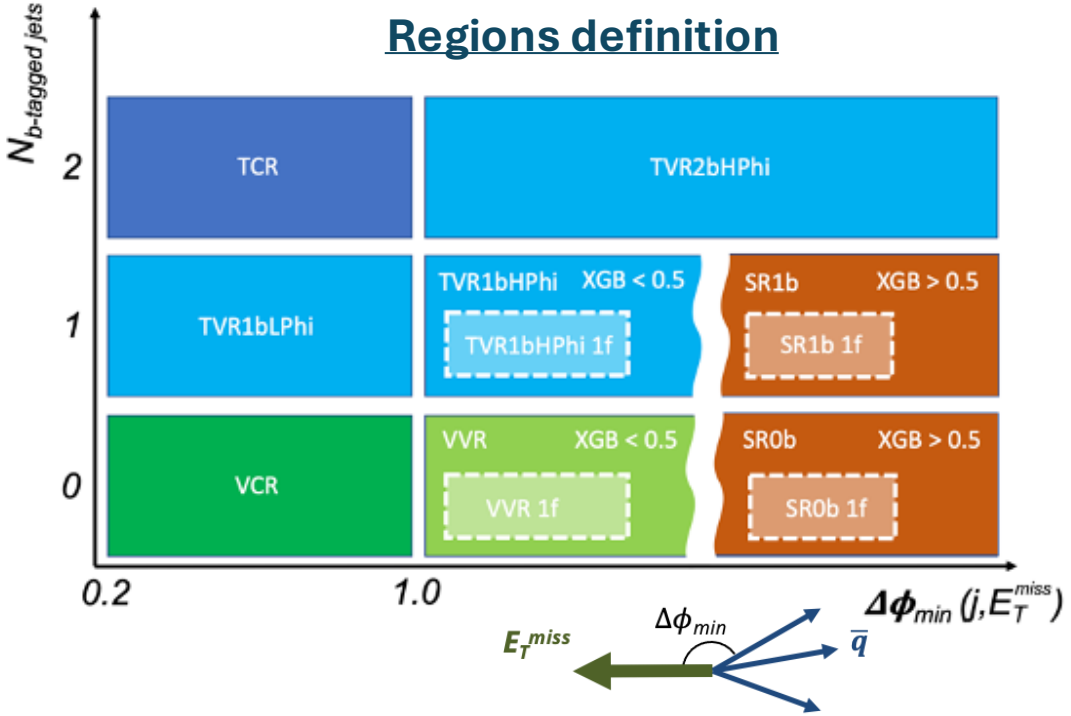


E_T^{miss} > 250 GeV

At least one top-tagged large-radius jet with p_T>350 GeV

- Lepton veto.
- $\Delta\phi$(jets,E_T^{miss}) > 0.2

Regions definition



Strategy

- Background estimation fitting to data in control regions.
- Boosted Decision Tree (BDT) to enhance sensitivity in signal regions.
- Likelihood fit in both control regions (yields) and signal regions (BDT).

Main backgrounds

Top pairs

W/Z+jets

Mono-top analysis

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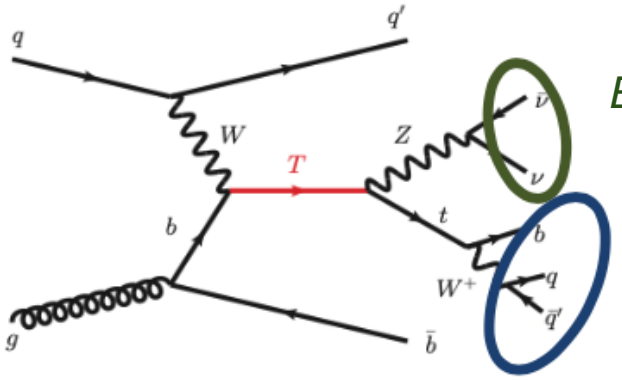
Preselection



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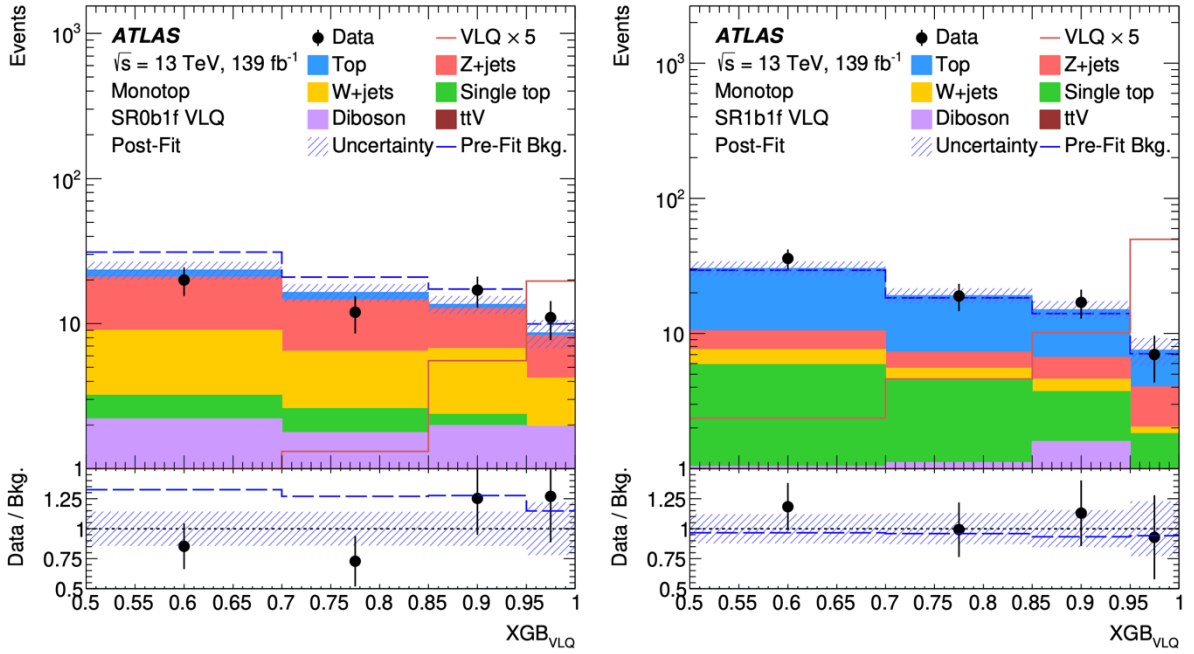
Signal regions



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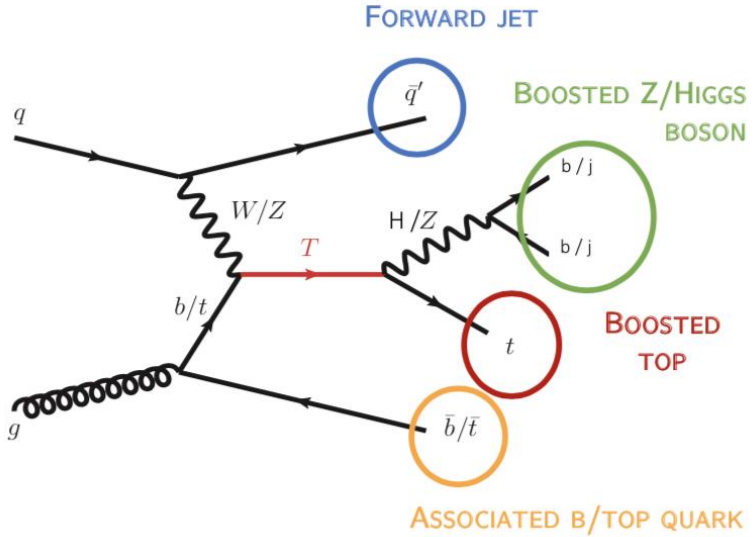
Ht/Zt analysis

Preselection

Publication: JHEP08(2023)153



Preselection requirements
Single-lepton or $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
=1 isolated e OR μ
≥3 jets
≥1 b-tagged jets
$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV
$m_{\mathrm{eff}} > 600$ GeV

Regions definition summary

		3-5 jets, ≥ 1 fwd-jet	≥ 6 jets, ≥ 1 fwd-jet
$T \rightarrow Zt$	1-2 b-jets	**0 t_h, 0/1 t_l, 0 H, ≥1 V**	**≥1 V or t_h/t_l, 0 H**
$T \rightarrow Ht$	≥ 3 b-jets	**0/1 t_h or t_l, ≥1 H, 0 V**	**≥ 1 t_h/t_l, 0/≥1 V, ≥ 1 H**
		b-associated	*t*-associated

Strategy

- Background estimation by reweighting at pre-fit level.
- Likelihood fit on the effective mass distributions.
- A total of 24 regions entering the fit.

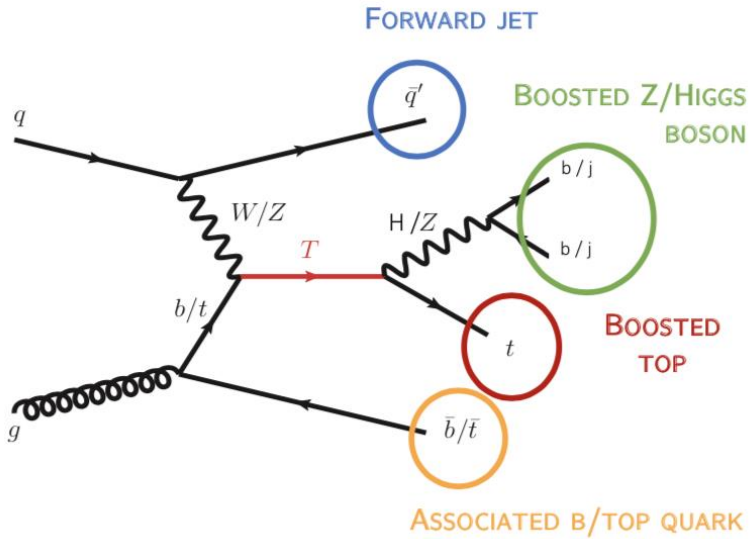
Main backgrounds

Top pairs + light-jets

Top pairs + c/b-jets

Ht/Zt analysis

Preselection



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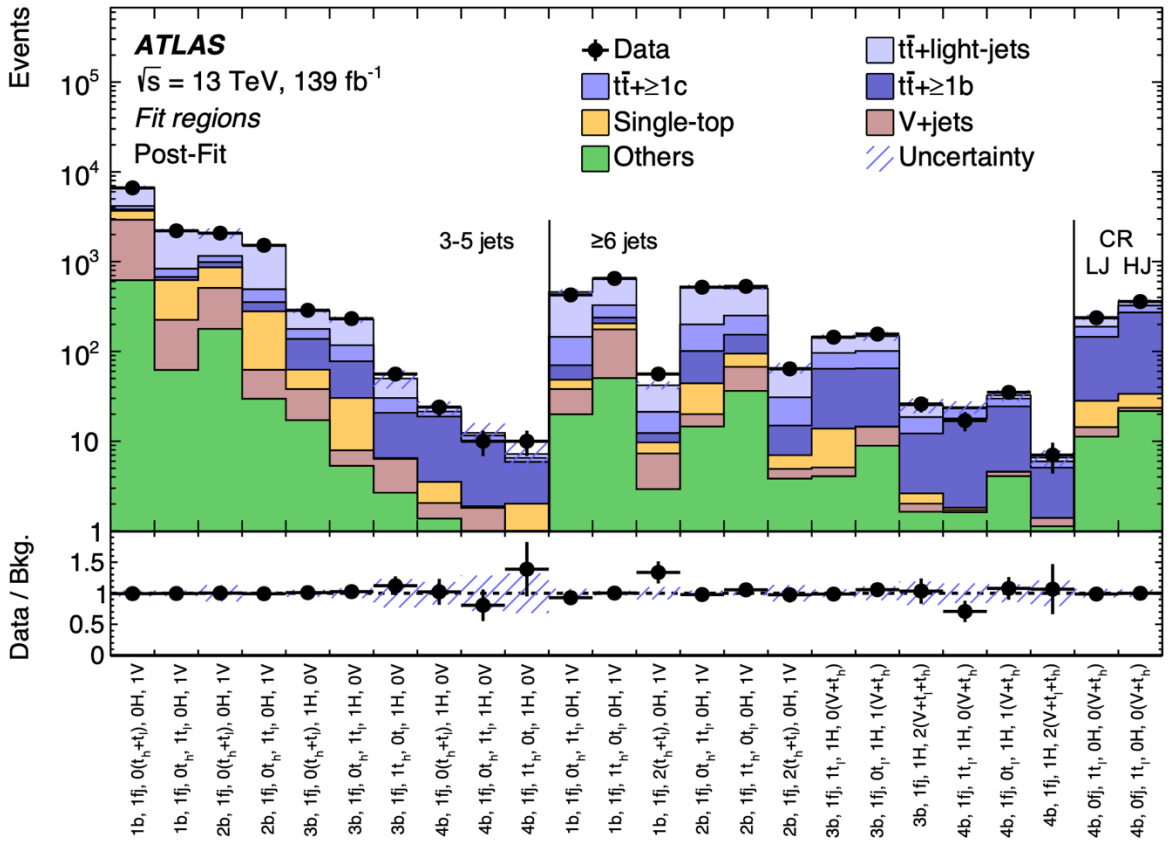
Publication: JHEP08(2023)153

Postfit yields summary

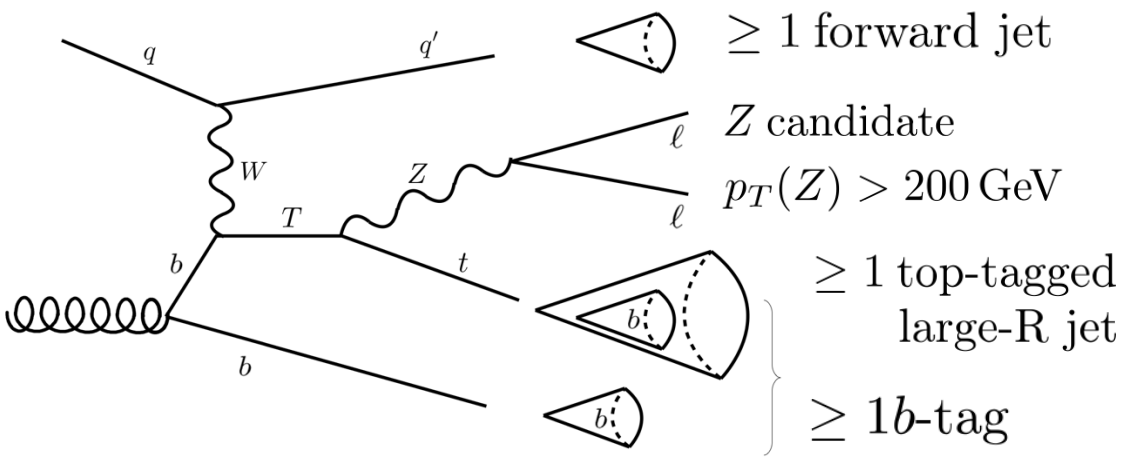


OSML analysis

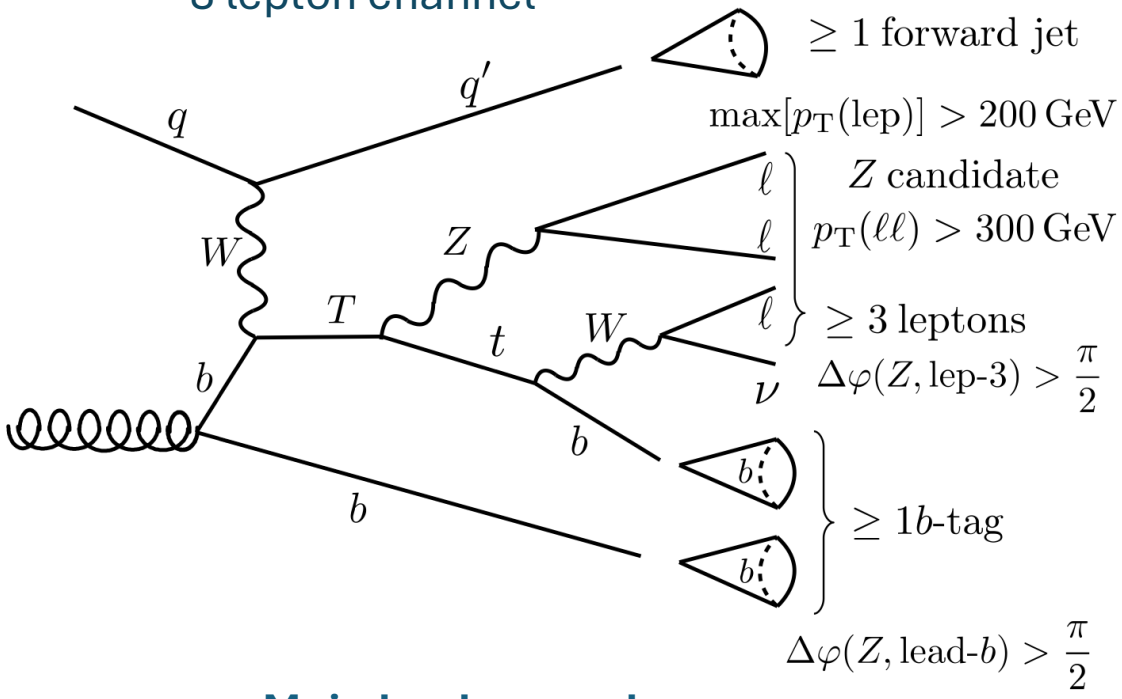
Preselection

Publication: PhysRevD.109.112012

2 lepton channel



3 lepton channel



Main backgrounds

Z+jets (light-flavour)

Z+jets (heavy-flavour)

Main backgrounds

Di-boson

Top pair + X

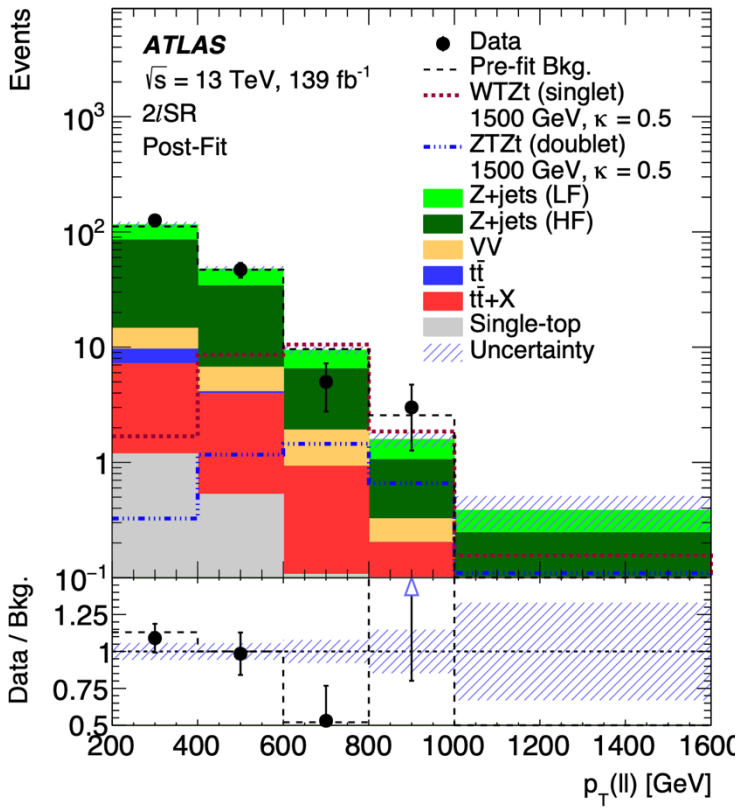
OSML analysis

Publication: PhysRevD.109.112012

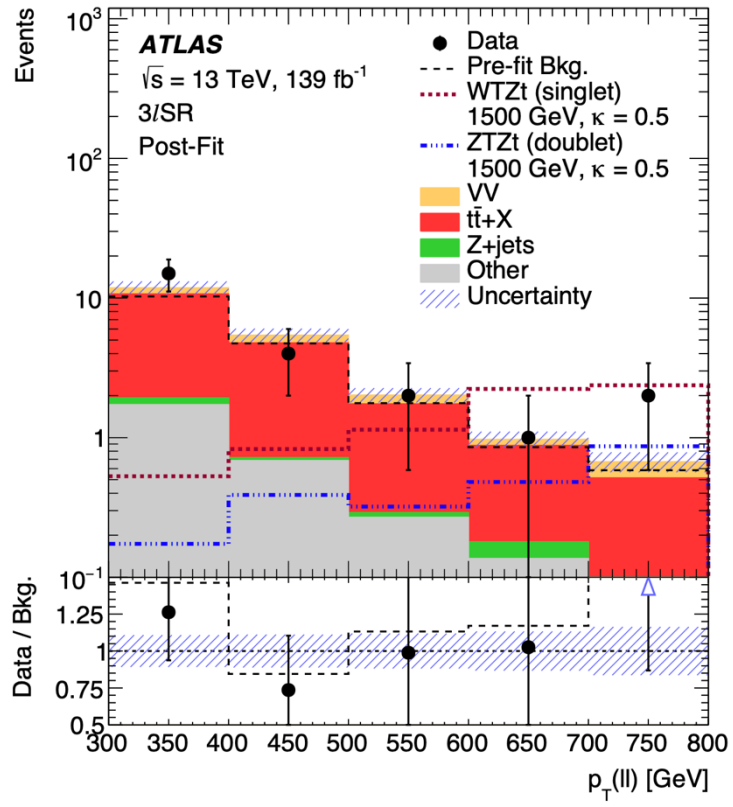
Strategy

- Reweighting techniques for background estimation.
- The two channels are statistically combined.
- Likelihood fit in the p_T distribution of the reconstructed di-lepton object.

2 lepton channel



3 lepton channel



Outline

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Channels analysed

Combination strategy and results

- Systematics treatment
- Improvement from individual analyses.
- Exclusion limits.

Conclusions

Combination strategy

- Histograms with the likelihood information (workspaces) generated with RooFit by each analysis.
- Combined workspace is built:
  - Common systematics are correlated among analyses.
  - Uncorrelated uncertainties for non-common systematics and unconstrained normalisation factors.
- Fitting to estimate an **inclusive signal strength**:
  - Zt -> T -> Zt
  - Zt -> T -> Ht
  - Wb -> T -> Zt
  - Wb -> T -> Ht

Publication: 2408.08789

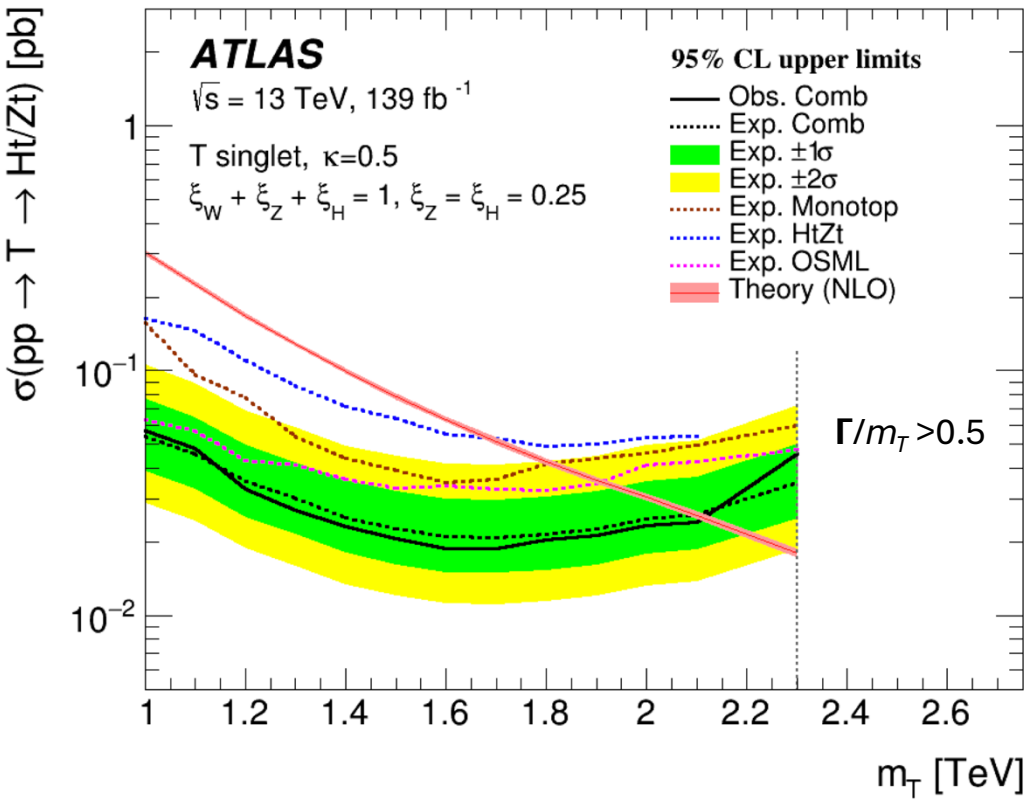
Systematics treatment

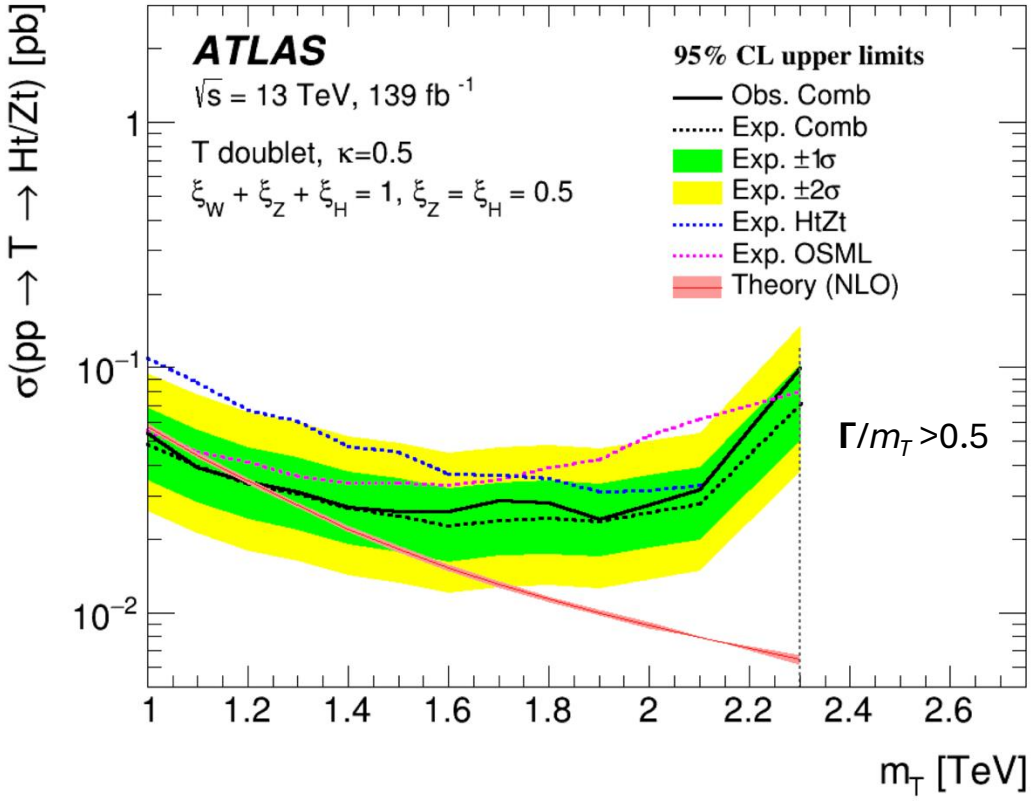
Category	MonoTop	HtZt	OsML	Correlating
Lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties				
Electron uncertainties		✓	✓	All
Muon uncertainties		✓	✓	All
$E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties	✓	✓	✓	All
Jet uncertainties				
JES uncertainties	✓	✓	✓	All
JER uncertainties	✓	✓	✓	HtZt and OsML
JMS uncertainties		✓		None
JMR uncertainties	✓	✓		None
Tagging uncertainties				
Flavor-tagging uncertainties	✓	✓	✓	MonoTop and OsML
Top-tagging uncertainties	✓			None
W/Z-tagging uncertainties	✓			None
Background modeling uncertainties (constrained)	✓	✓	✓	None
Background normalization factors (unconstrained)				
$t\bar{t}$ normalization	✓			None
V+jets normalization	✓			None
Z+light-jets normalization			✓	None
Z+heavy-flavor normalization			✓	None
$t\bar{t}V$ normalization			✓	None
VV normalization			✓	None

Results

Publication: 2408.08789

- No significant excess over the prediction has been found.
- The combination significantly improved the limits on the SU(2) singlet (doublet).
  - The excluded cross-section decreased around a 50% (20%).
  - The mass limit increased around 200 (150) GeV.

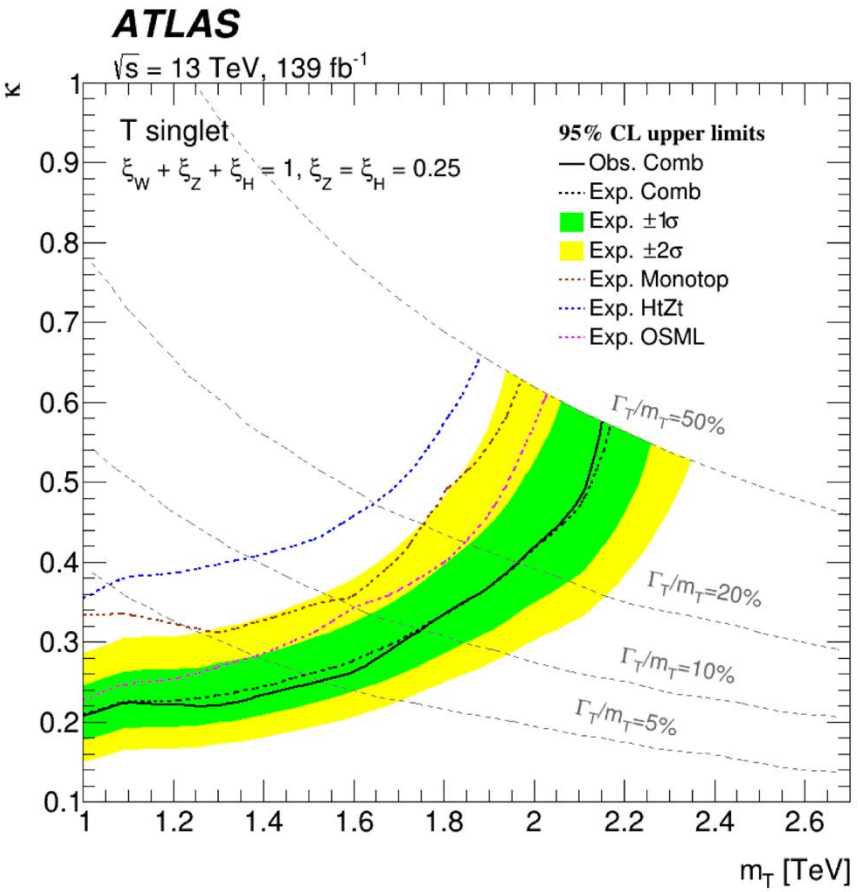


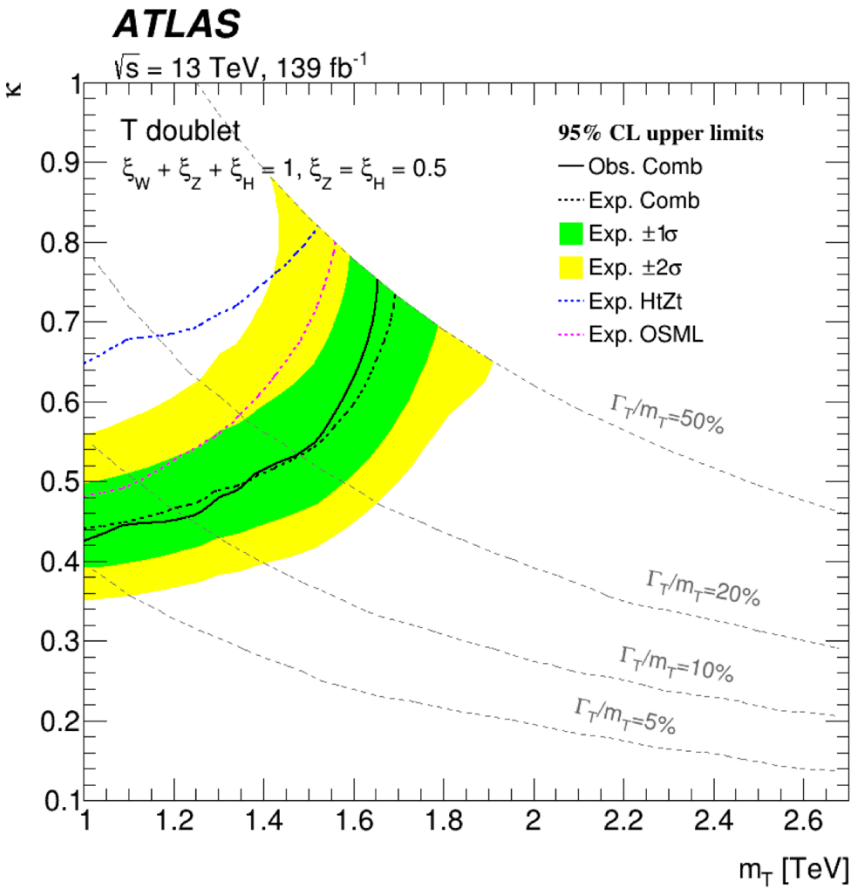


Results

Publication: 2408.08789

- Upper limits set for m_T:
  - Singlet: m_T excluded up to 2.1 TeV for $\kappa \sim 0.5$.
  - Doublet: m_T excluded up to 1.6 for $\kappa \sim 0.7$.
- Upper limits set for κ:
  - Singlet: $\kappa > 0.25$ excluded for $m_T < 1.6$ TeV.
  - Doublet: $\kappa > 0.5$ excluded for $m_T < 1.4$ TeV.

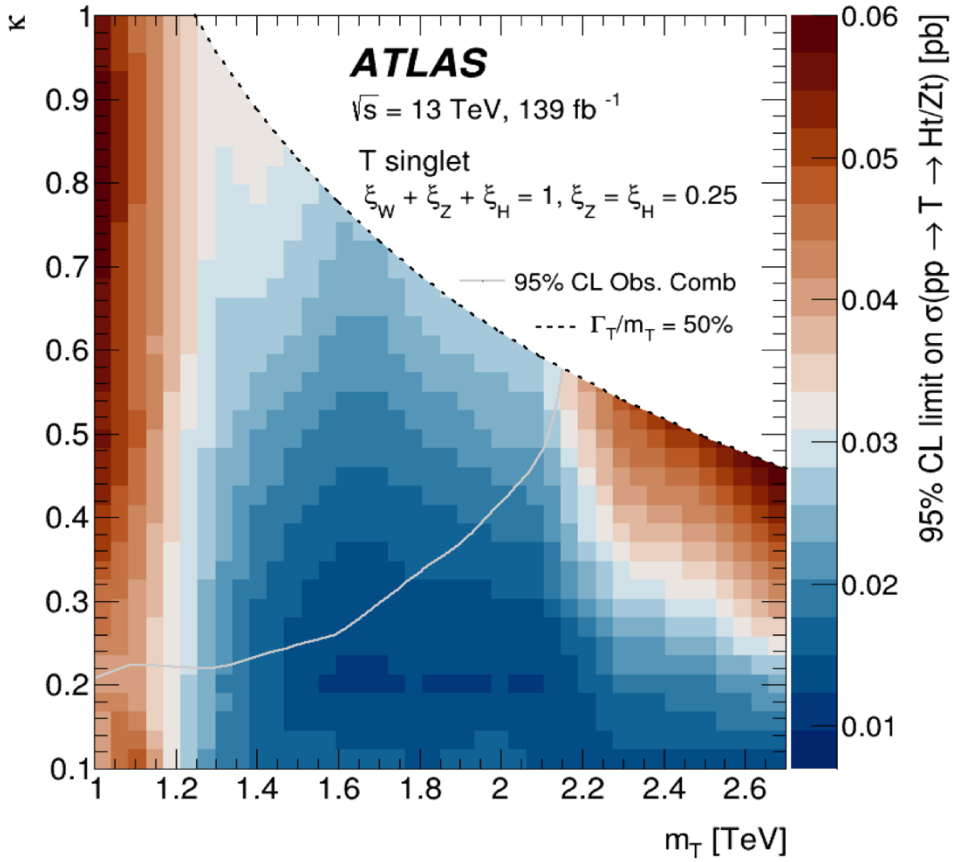


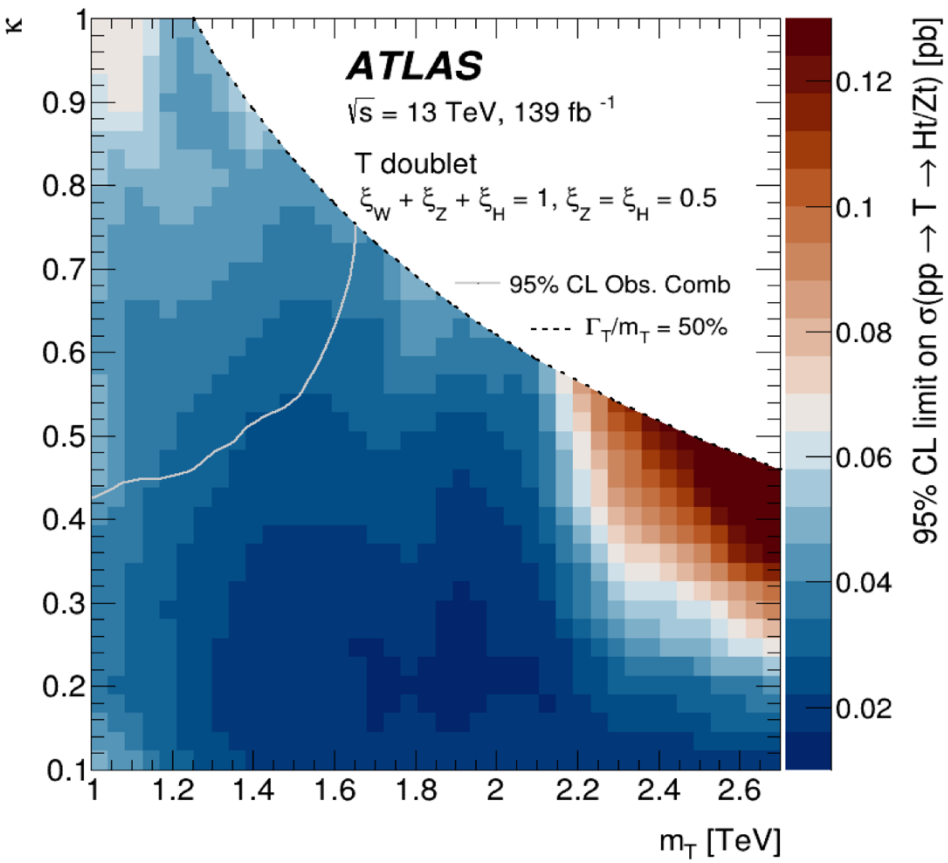


Results

Publication: 2408.08789

- Upper limits on the cross-section:
  - Singlet: $\sigma(\kappa, m_T) > 0.02$ pb excluded for $\kappa \sim 0.3$ and $m_T \in [1.4 , 1.8]$ TeV.
  - Doublet: $\sigma(\kappa, m_T) > 0.02$ pb excluded for $\kappa \sim 0.5$ and $m_T < 1.4$ TeV.



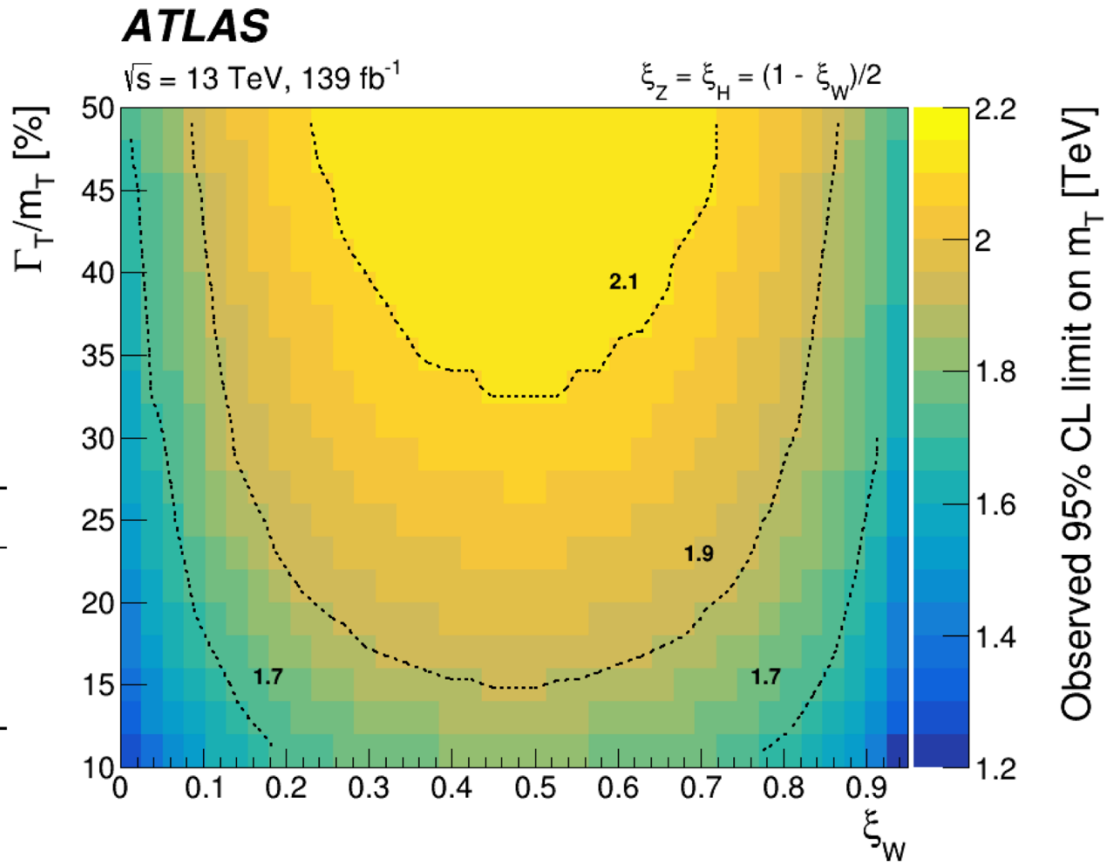


Results

Publication: 2408.08789

- Limits can be generalised for arbitrary values of ξ_W .
- ξ_W = BR(T->Wb) = 0.5 (0.0) correspond to the singlet (doublet) interpretation.
- Singlet scenario provides the best sensitivity.

Representation	Γ_T/m_T [%]	Obs./Exp. mass limit [TeV]
SU(2) singlet ($\xi_W = 0.5$)	20	2.0 / 2.0
SU(2) singlet ($\xi_W = 0.5$)	50	2.1 / 2.1
SU(2) doublet ($\xi_W = 0.0$)	20	1.4 / 1.4
SU(2) doublet ($\xi_W = 0.0$)	50	1.6 / 1.7



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Channels analysed

Combination results

Conclusions

- Summary and impact of the results.

Conclusions

- This is the first combination of singly produced VLQ searches in ATLAS.
- Three channels producing a single Vector-like Top quark are combined.
  - Mono-top: JHEP05(2024)263.
  - Ht/Zt: PhysRevD.109.112012.
  - OSML: JHEP08(2023)153.
- No significant excess over the Standard Model predictions are observed.
- 95% CL upper limits obtained for SU(2) singlet (doublet) T-quark scenario.
  - **The limits improved significantly with respect the individual searches.**
  - The excluded cross-section decreased by a factor 2 in some cases (> 0.02 pb).
  - The m_T *is* excluded up to 2.1 (1.6) TeV for κ values around 0.5 (0.7).
  - κ values above 0.25 (0.5) are excluded for m_{VLT} below 1.6 (1.4) TeV.
- This paper presents the most stringent limits on the Vector-like Top quarks to date.
  - Publication (already accepted by PRD): 2408.08789

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  - The excluded cross-section decreased by a factor 2 in some cases (> 0.02 pb).
  - The m_T *is* excluded up to 2.1 (1.6) TeV for κ values around 0.5 (0.7).
  - κ values above 0.25 (0.5) are excluded for m_{VLT} below 1.6 (1.4) TeV.
- This paper presents the most stringent limits on the Vector-like Top quarks to date.
  - Publication (already accepted by PRD): 2408.08789

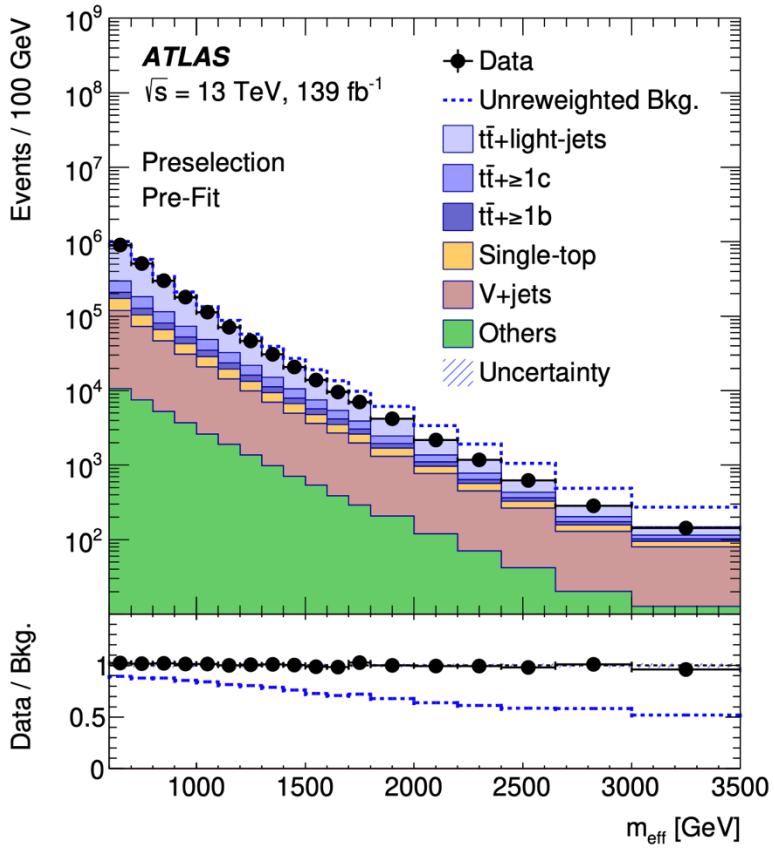
Back up

HtZt reweighting

- Overestimation of the top pair cross section at high p_T of the top quark, and underestimation at high multiplicity of jets.
- Iterative reweighting factors extracted from the Njets and the meff distributions in dedicated subregions.

$$R_a(x) = \frac{\text{Data}(x) - \text{MC}^{\text{non-}a}(x)}{\text{MC}^a(x)}$$

Reweighting source regions				
Lepton multiplicity	Jet multiplicity	b-tag multiplicity	Other requirements	Targeted background
1	≥3	2	–	$t\bar{t} + tW$
2	≥3	1	$\lvert m_{\ell\ell} - m_Z \rvert \leq 10$ GeV, $E_{\text{T}}^{\text{miss}} < 100$ GeV	Z+jets



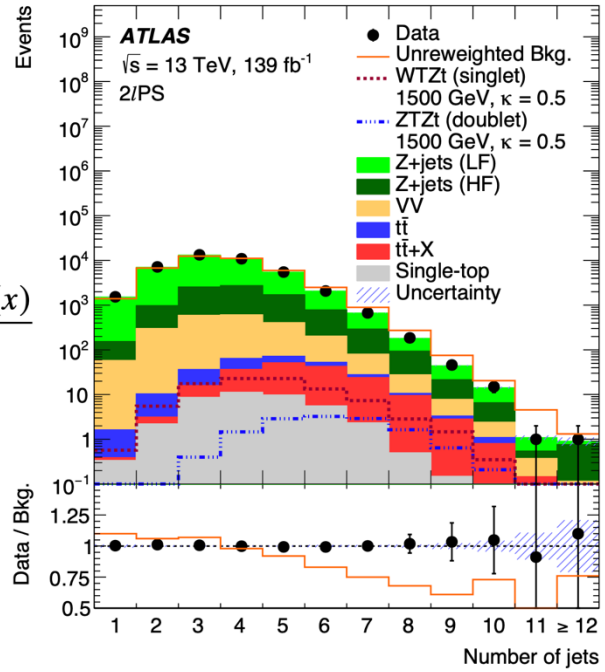
OSML analysis reweighting

Publication: PhysRevD.109.112012

2 lepton channel

Reweighting

$$R_{\text{Z+jets}}(x) = \frac{\text{Data}(x) - \text{MC}^{\text{non-Z+jets}}(x)}{\text{MC}^{\text{Z+jets}}(x)}$$



Main backgrounds

Z+jets (light-flavour)

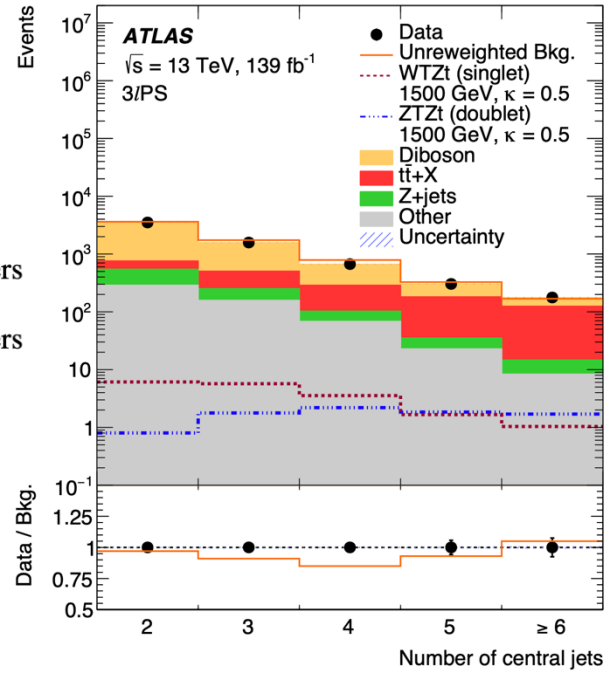
Z+jets (heavy-flavour)

3 lepton channel

Reweighting

$$n_{0,i}^{\text{data}} = \alpha_i^{VV} n_{0,i}^{VV} + \alpha_i^{ttX} n_{0,i}^{ttX} + n_{0,i}^{\text{others}}$$

$$n_{1,i}^{\text{data}} = \alpha_i^{VV} n_{1,i}^{VV} + \alpha_i^{ttX} n_{1,i}^{ttX} + n_{1,i}^{\text{others}}$$



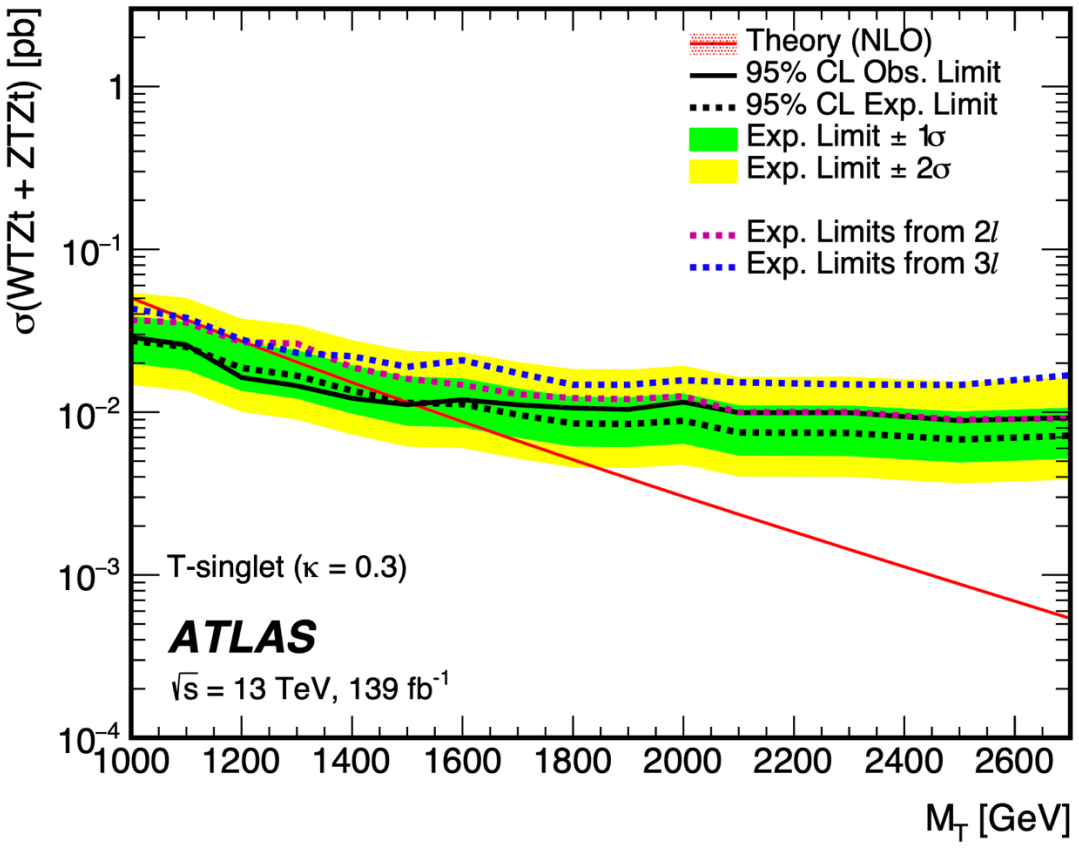
Main backgrounds

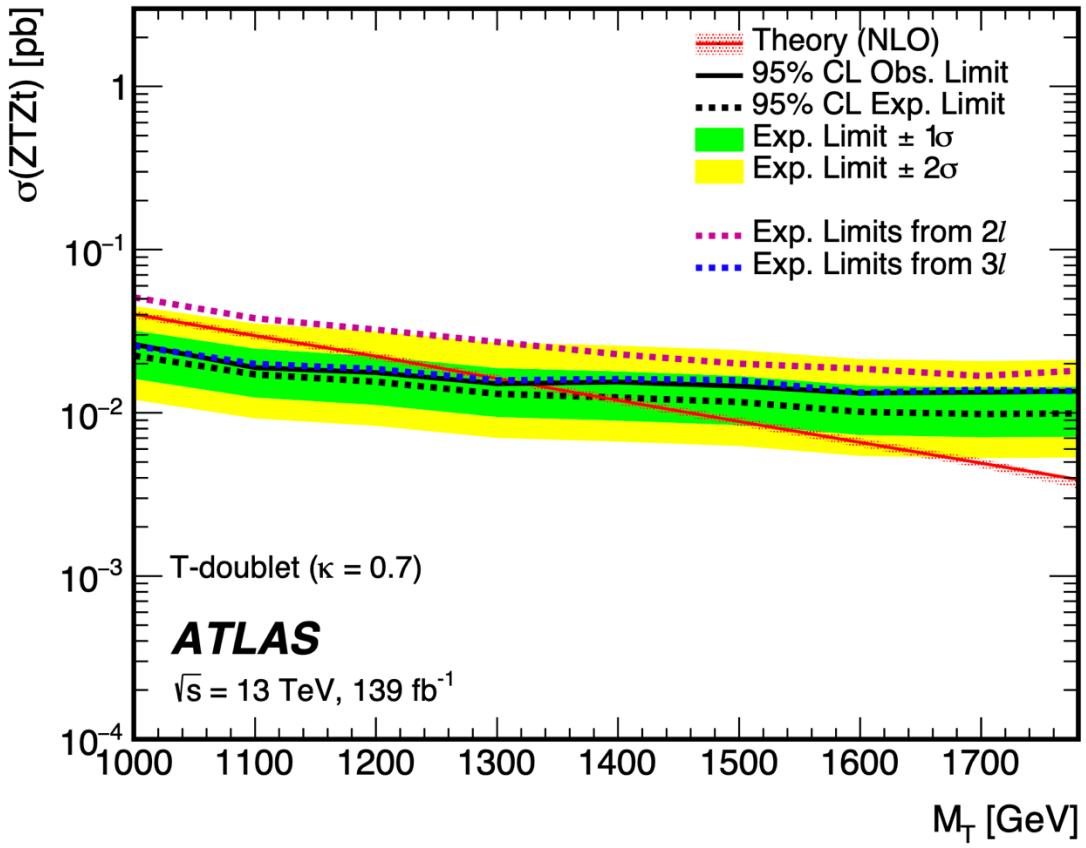
Di-boson

Top pair + X

OSML combination

- The combination improves the sensitivity with respect to the individual analyses.
- Mass limit on the singlet interpretation improves around 200 GeV.





Summary of CMS limits